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13. SUPPLEMENTARY NOTES This was a joint research project between UCSB and Auburn University (Dr. N. Hari Narayanan N00014-96-1-1187). The final report describes work carried out primarily at UCSB, but also reflects the collaborative nature of the research.					
14. ABSTRACT We developed a cognitive model of how people encode information and make inferences from multimedia presentations and conducted empirical studies to validate different aspects of this model in the domains of mechanics and computer algorithms (more recent empirical studies have begun to generalize this model to the domain of meteorology). This model was then used to derive general guidelines for authoring interactive visualizations to support human performance. We developed and evaluated several versions of multimedia information presentations that conformed to these guidelines in the domains of mechanical and computer algorithms. Our experiments showed that information presentations designed according to our guidelines were more effective than information presentations that do not conform to these guidelines. Our research also indicated that there is no advantage of computer-based presentations, including animations, over paper-based presentations, with static diagrams, when both are designed according to our empirically-validated guidelines. The report also summarizes some preliminary empirical studies in which we extended our model of multimedia comprehension to the domain of meteorology.					
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Final Report  
Grant N00014-96-1-0525  
Analysis and Synthesis of Hypermedia Visualizations  
Mary Hegarty,  
University of California, Santa Barbara

Note: This report is structured in the same format as ONR annual performance and progress reports. However the order of items are somewhat different. Each section contains relevant cumulative information over the entire project period of August 1 1996 to December 31, 2002.

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Dr. N. Hari Narayanan, Auburn University

This was a joint research project between University of California, Santa Barbara (Dr. Mary Hegarty, PI, grant N000149610525) and Auburn University (Dr. N. Hari Narayanan, PI, grant N000149611187). The final report from each of these institutions describes research and dissemination activities carried out at that university in more detail. Therefore the reports are not identical, however, there is considerable overlap reflecting the joint nature of the research.

### **3. Long Term Goals of the Project**

3.1 To develop a theory of the cognitive processes involved in understanding diagrams and other visualizations of causal systems and making inferences from these visualizations

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3.2 To translate this knowledge into practical guidelines for designing visualizations of causal phenomena and to validate the guidelines by designing and testing prototypes.

#### **4. Scientific and Technical Objectives**

4.1 To understand how novices and experts comprehend complex visualizations in domains such as mechanics and meteorology and how they make causal inferences from these visualizations.

4.2 To develop design principles for interactive visualizations in these complex domains and to build and evaluate prototypes embodying these principles.

#### **5. Approach**

5.1 Developing a model of how experts and novices comprehend and make inferences from complex visualizations

5.2 Testing and developing this model by conducting empirical studies of how experts and novices comprehend and make inferences from complex visualizations. These studies involve collection and analysis of several different types of data, including problem solving accuracy, response times, eye-fixation protocols, and verbal protocols.

5.3 Development of design principles for interactive visualizations that support human performance, based on the model and empirical studies described above.

#### **6. Concise Progress Summary**

##### **6.1 A Preliminary Model of Comprehension and Inference from Complex Visualizations**

In research conducted with funding from the Office of Naval Research in the last 6 years, we have developed a model of how people understand and make inferences from multimedia presentations (Narayanan & Hegarty, 1998; Hegarty, Quilici, Narayanan, Holmquist and Moreño, 1999). This model was initially developed in the domain of mechanics and has been generalized to the domains of computer algorithms (Hansen, Narayanan & Hegarty, 2002) and meteorology in more recent research.

According to this model, people construct a mental model of a dynamic system (e.g. a machine) by first decomposing it into simpler components, retrieving relevant background knowledge about these components, and mentally encoding the relations (spatial and semantic) between components to construct a static mental model. They then mentally animate this static mental model to construct a kinematic/dynamic mental model of the system. We postulate that mental model construction under these circumstances

requires the stages described below. Although we list them in order, we acknowledge that they are not always accomplished in this order.

*A. Machine Decomposition by Diagram Parsing.* Diagrams of mechanical systems are made up of elementary shapes, such as rectangles, circles and cylinders, which represent objects such as pistons, gears and tubes. The first step in comprehension is to parse the connected diagram into these elementary shapes, i.e., units in the diagram that correspond to subcomponents of the mechanical system.

*B. Constructing a Static Mental Model by Making Representational Connections.* The second stage in multi-modal comprehension involves making appropriate connections in memory among the components identified in Stage 1. This stage involves making two types of connections: (1) connections to prior knowledge and (2) connections to the representations of other machine components.

First, the user must identify the components, that is, make connections between the diagrammatic elements identified at Stage 1 and their real-world referents. For example, the user might represent that a rectangle represents a piston or a circle represents a gear. Prior knowledge can also provide additional information about components, such as what they are typically made of and whether they are rigid or flexible. This information is valuable in making inferences about how components move and constrain each other's behaviors.

Second, the user must represent the spatial relations between different machine components by building connections between the representations of these components (Mayer & Sims, 1994). In understanding how a machine works, information about the spatial relations between mechanical components forms the basis for inferences about the motions of components, because these spatial relations determine how components affect and constrain each other's motions.

*C. Making Referential Connections.* When diagrams are accompanied by text, an additional stage in comprehension is that of resolving coreference between the two media, i.e., making referential links between a noun phrase in the text (e.g., "the piston") and the diagrammatic unit that depicts its referent (e.g., a rectangle) (Novak, 1995). This step is crucial to constructing an integrated representation of the common referent of the text and diagram in memory as opposed to separate surface-level representations of the text and diagram.

*D. Determining the Causal Chain of Events.* When asked to predict the behavior of machines from static diagrams, people tend to reason about machine operation along the direction of causal propagation in the machine (Hegarty, 1992; Narayanan, Suwa & Motoda, 1994; 1995). Therefore, we hypothesize a fourth stage of comprehension that involves identifying the potential causal chains of events in the operation of the machine, or "lines of action" in the machine.

*E. Constructing a Dynamic Mental Model by Mental Simulation and Rule-based Inference.* The final stage of comprehension is that of constructing a dynamic mental model of the machine, i.e., a representation of how the components move and constrain each other's motion when the machine is in operation. Our previous research (Hegarty, 1992; Narayanan, Suwa & Motoda, 1994; 1995) suggests that people can often infer this information from a static diagram by a process called mental animation. Computational models and empirical evidence suggest that this is an incremental process in which the reasoner considers the components or subsystems individually, assesses the influences acting on each, infers the resulting behavior of each, and then proceeds to consider how this behavior affects the next component or subsystem in the causal chain. It depends on both prior knowledge (e.g., rules that govern the behavior of the system in question) and spatial visualization processes.

## **6.2 Basic Research on Comprehension and Inference from Complex Visualizations in the domain of Mechanics.**

One of the goals of this grant was to test and develop this model by conducting empirical studies of how experts and novices comprehend and make inferences from complex visualizations. These studies involve collection and analysis of several different types of data, including problem solving accuracy, response times, eye-fixation protocols, and verbal protocols. They were conducted in the domains of mechanics and meteorology.

**Research in the Domain of Mechanics.** Our model of machine comprehension suggests that an important component of machine comprehension is that of understanding the causal chain of events in the operation of the machine. This can be a source of comprehension failure, especially in complex machines in which several components move at once and there are more than one causal chain of events or "lines of action in the machine. On prediction of our model therefore is that people will have superior comprehension of mechanical systems if the components of the device are highlighted in order of the causal chain of events in the operation of the system.

Four experiments at Auburn University used eye-fixation analyses to examine mental animation of static displays of complex causal mechanisms with branching and merging causal chains. The first experiment replicated and extended our previous research on mental animation, showing that successful students follow the causal chain of events in a machine when mentally animating a mechanical system. In the next experiment we collected baseline data on accuracy and response time of subjects making predictions from diagrams of complex causal mechanisms with branching and merging causal chains. The third experiment examined whether highlighting the components of the device in order of this causal chain of events affects performance. Highlighting improved performance on the problems (the group who received highlighting had an accuracy rate of 60% compared to 40% for the control group) but also lead to more time on task. In the fourth experiment, the effects of highlighting were replicated with less expert participants

Another prediction of our model is that because people can mentally animate mechanical systems to some extent, they will learn more from both multimedia



presentations if they attempt to mentally animate static diagrams of mechanical systems before viewing animations of how these machines work, or learning from printed (text and diagram) materials explaining how these machines work. Three experiments at University of California, Santa Barbara investigated the effects of mental animation on learning from multimedia and printed presentations that explain how machines work. These experiments showed that people learn more from multimedia presentations if they first try to mentally animate the machines in question. We conducted extensive analyses on the results of three experiments on the effects of mental animation on learning from multimedia, including precise characterizations of the mental models of individuals who learned from the different media. A paper summarizing this work was accepted for publication in *Cognition and Instruction* (Hegarty, Kriz & Cate, in press).

In collaboration with researchers at the Applied Physics Laboratory, University of Washington, we conducted an additional experiment that investigated whether people learn more from multimedia presentations explaining how machines work if the presentations show realistic, 3d diagrams of the mechanical systems rather than 2D cross-sectional views. We had two professionally authored multimedia presentations built for testing. These manuals, one using 2D and the other using 3D graphics, explain a relatively complex but familiar device: the flushing cistern. These manuals incorporate all the design guidelines developed in our research so far. In an experimental evaluation of these manuals at UCSB, we varied (1) whether students learned from the hypermedia manuals or merely from a labeled diagram of the machine and (2) whether they received 2-d or 3-d diagrams in their training. Results indicated that those who received the hypermedia visualizations had superior comprehension of the machine, but there was no difference between those who received 2-d and 3-d views.

The grant also provided partial funding for several other related basic-research projects that examined the roles of spatial abilities and working memory in mechanical reasoning. In one project (Hegarty, 2000) I examined the working-memory demands involved in mental animation of simple machines, using the 3CAPS production system architecture. This research suggested that both spatial and executive working memory systems are involved in mental animation. Another project (Miyake, Rettinger, Friedman, Shah & Hegarty, 2001) established the relation between these working memory systems and complex spatial visualization abilities, which are known to be involved in mechanical reasoning.

Other research projects examined the relation of spatial abilities to various forms of physics problem solving, including mental animation (Kozhevnikov, Hegarty & Mayer, 2002a; 2002b). This research indicated the necessity to distinguish between spatial abilities involved in imagining manipulations of objects and spatial abilities involved in imagining different perspectives in space (Kozhevnikov & Hegarty, 2001a). Finally, we conducted a literature review in which we compared and contrasted research on explicit knowledge about mechanical phenomena, as revealed by naïve physics studies, and implicit knowledge, as revealed by studies of the perception of moving stimuli (representational momentum) (Kozhevnikov & Hegarty, 2001b).

### **6.3 Design principles for interactive visualizations, based on the model and empirical studies described above.**

The comprehension model and empirical research described above suggested the following general design guidelines for interactive visualizations that support human performance.

- (1) *The decomposition guideline*: provide cues in verbal and visual representations that help users decompose the system or process being explained into simpler components.
- (2) *The prior-knowledge guideline*: use words and pictures that help users invoke and connect their prior knowledge to the external representations.
- (3) *The co-reference guideline*: use interactive and deictic devices to highlight the common referent when multiple verbal and visual references in different media refer to the same object or component.
- (4) *The lines-of-action guideline*: use words and pictures that help a user understand the physical, causal and logical connections among parts that determine how the behavior of each part of the system or process influences that of others.
- (5) *The mental simulation guideline*: use graphics and interactivity to encourage users to predict, or mentally simulate, the process or system that is being explained before providing an external animation.
- (6) *The basic principles guideline*: When the operation of a system depends on basic principles that might not be understood by all users, describe these principles explicitly in the context of the system being explained.

### **6.4 Development and testing of prototype visualizations based on the design principles.**

Following the design guidelines outlined above, we developed two different hypermedia presentations, one in the domain of mechanics and the other in the domain of computer algorithms (the latter presentation was developed in part with funding from the National Science Foundation to Dr. Narayanan). Details of the structure of these manuals are described by Narayanan & Hegarty, (2002).

We conducted several experiments comparing these hypermedia to (1) informationally equivalent printed manuals that also conformed to these design guidelines (3) animations typical of extant research and commercial CD-ROMS, and (4) mixed-mode explanations extracted from commercial books. First, we found that manuals designed according to our guidelines are more effective than manuals that do not conform to these guidelines (both commercial and research products) (Narayanan & Hegarty, 2002; Hegarty, Narayanan & Freitas, 2002). Second, we found different results across domains with respect to the question of whether computer-based dynamic hypermedia presentations are more effective than informationally equivalent static paper-based presentations. In the physical domain of mechanics, computer-based dynamic presentations were not superior to printed presentations. In the abstract domain of algorithms, computer-based dynamic presentations were superior (Narayanan & Hegarty, 2001; Hampson, Narayanan & Hegarty, 2002).

## 6.5 Basic Research on Comprehension and Inference from Complex Visualizations in the Domain of Meteorology.

One of the important goals of the research funded by this grant was to start to generalize our model of comprehension of complex visualizations in the domain of mechanics to the new of meteorology. There are several differences between these two domains. First, visualizations in the domain of meteorology are much more complex than in the domain of mechanics. For example, typical displays in this domain (weather maps) often superimpose as many as 7 or 8 different variables on the same map. Second, the displays are more abstract – although diagrams of machines show physical (visible) objects, weather maps often use visual variables (color, lines etc.) to represent non-visible properties such as temperature and pressure. Third, inferences from weather maps depend more on knowledge of the domain (compared to mechanical inferences which can be made by general mental animation processes) so that a key question in this domain is how people apply their domain knowledge of meteorological principles to the interpretation of weather maps. Therefore our experiments in this domain have focused on the comprehension and inference processes of people with different amounts of domain knowledge of meteorology.

In our initial 3 experiments at UCSB we examined naïve students' comprehension of weather maps from US newspapers. *Naïve* students are those who have received no formal education in meteorology. In these experiments, we manipulated the number of variables (pressure, temperature, precipitation) shown on the maps and assessed how this affected students descriptions of the weather and their verification of statements about the weather in different locations. Students' descriptions were very literal descriptions of the specific variables shown on the maps. They rarely related two or more variables or made any inferences from the information displayed. They were slower to verify a fact about a particular variable when more variables were shown on the map.

In further experiments, we examined people's ability to make inferences (weather forecasts) about changes in temperature from maps showing pressure and temperature patterns across the United States. In these experiments we compared performance of experts (meteorologists at a Naval Research Laboratory), novices (geography students who had taken one course in meteorology) and naïve students (psychology students with no formal training in meteorology).

The experts were extremely consistent in their predictions, indicating that there is an agreed-upon correct prediction for each task. Novices and naïve individuals were compared on their ability to make these predictions and their knowledge of the underlying meteorology principles on which the predictions are based. Although almost all novices were able to state the principles correctly, and were much superior to naïve individuals on this measure, the two groups did not differ on their ability to make inferences from the weather maps. Overall performance on the prediction task was just a little above chance.



Based on verbal protocols and patterns of responses across different problems we identified the specific causal principles used by each student in making his/her predictions. Results indicated that whereas students can articulate individual causal principles of weather (e.g. air moves from areas of high pressure to areas of low pressure), they have considerable difficulty in integrating and applying multiple causal principles to accurately predict weather events. A further experiment showed that their failure to make inferences from the maps was not due to a failure to activate the relevant knowledge (reminding students of the relevant knowledge did not affect their performance).

In the two further experiments we developed multimedia instruction to teach meteorology principles to naïve students and varied whether or not the principles were explained in the context of a weather forecasting problem. In these experiments, we were successful in teaching the principles to naïve students, but unsuccessful in teaching these students to apply the relevant knowledge to making inferences from weather maps. These studies suggest that knowledge of relevant causal principles and ability to comprehend a weather map are not sufficient conditions for being able to make inferences from weather maps.

Finally, we designed and implemented a web-based interactive weather map display program in Javascript that allows a user to selectively overlay or hide one of several meteorological variables such as pressure, temperature and dew point. The program logs all user interactions. A companion program was developed that could parse these logs and replay the interactions of specific users so that the experimenter could get a qualitative understanding of the actions of each user. This system was used in an experiment at UCSB to elucidate novice strategies for presentation of meteorological variables when reasoning about weather phenomena involving multiple variables. Analysis of data from this experiment is in progress. Our goal is to produce a model of novice strategies.

## **6.6 Development of Eye-Tracking Laboratories**

We set up eye-tracking laboratories with two trackers from SMI Inc. at both UCSB and Auburn University. This equipment was purchased with funds from a related DURIP grant. This included several technical developments as follows:

1. We developed software for presenting stimuli and collecting eye-fixation data in experimental studies
2. Software for visualizing eye-fixation data, i.e. replaying the stimulus that a participant in an experiment had viewed, while overlaying his or her eye fixations on that stimulus
3. Software for analyzing eye-fixation data, i.e. defining "regions of interest" in a visual display and examining the frequency, order and duration of fixations on those regions of interest.

This software was used in 4 experiments at Auburn and 2 experiments at UCSB to date. Several experiments have been concerned with the effects of attentional cues in diagrams and animations on directing observers' eye fixations to the most relevant areas of a visual display and on the effects of these attentional cues on problem solving and learning from multimedia displays. One other experiment examined the relation between students' eye fixations and their verbalizations when they solved mechanical troubleshooting problems and gave "think aloud" protocols.

We also accomplished some further development of a program called the Restricted Focus Viewer (RFV), developed at Monash University in Australia. It follows a user's mouse movements and only reveals parts of a stimulus image around the cursor location while hiding the rest of the image. It is a relatively inexpensive alternative to using an actual eye tracker, and does not suffer from some of the limitations one faces when using the eye tracker in an experiment. It allows us to easily carry out pilot studies in eye tracking before running actual eye tracker experiments. This was accomplished by inviting the author of the RFV, a Computer Science student at Monash University, to visit Dr. Hegarty's lab for a month in summer. This software was used in two experiments at UCSB to examine information-seeking patterns of novices when they scanned weather maps from US newspapers in order to verify a specific fact about the weather in different locations

Finally, an interactive data analysis and visualization program, called RFVDAT, was developed at Auburn to parse data from the RFV. This program allows the experimenter to select any regions of interest on the stimulus and receive data how long the subject spent viewing these regions of interest, the order in which they viewed these regions etc.

### **6.7 Dissemination:**

Our research was disseminated through 11 journal articles, 3 book chapters, and 6 peer-reviewed conference presentations. We also made several invited presentations on our work as listed below

### **7. Best Accomplishments**

- The development of a cognitive model of multimodal comprehension.
- The generation and dissemination of guidelines for the design of multimedia information presentations.
- Design and evaluation of several versions of multimedia manuals that conform to the cognitive model and design guidelines.
- The experimental demonstration that manuals (computer-based or printed) designed according to our guidelines are more effective than manuals that do not conform to these guidelines (both commercial and research products) in the two domains of machines and computer algorithms (Narayanan & Hegarty, 2002).

- Experimental demonstration that when a text-and-diagram presentation is designed according to principles that we have so far developed in our research, it does not have to be delivered on a computer (i.e. it can be paper-based) in order to effectively support the comprehension and inference tasks in the mechanical domain (Narayanan & Hegarty, 2002; Hegarty, Narayanan & Freitas, 2002; Hegarty, Kriz & Cate in press).
- Experimental demonstration that when a text-and-diagram presentation in the mechanical domain is designed according to principles that we have so far developed in our research, it does not matter whether a 2-d or 3-d diagram is shown.
- Demonstration that attentional cues in diagrams (that guide attention to information as it is needed for problem solving) can enhance human problem solving performance.
- Demonstration that people learn more from both dynamic computer-based animations and static text and diagrams describing how machines work if they first mentally animate static diagrams of these machines (Hegarty, Kriz & Cate, in press).
- Experimental demonstration that although novices can articulate individual causal principles in the domain of meteorology, they have considerable difficulty in integrating and applying multiple causal principles to accurately predict a weather event. Therefore, (1) ability to understand a visualization, and (2) knowledge of relevant causal principles are not sufficient conditions for making causal inferences from weather maps. Thus, although novices can articulate individual causal principles in the domain of meteorology, they have considerable difficulty in integrating and applying multiple causal principles to accurately predict a weather event.
- Experimental demonstration that naïve students' descriptions and interpretations of weather maps are influenced by the number of variables shown on the maps.

## **8. Impact/Applications**

### **I. Impact of Basic Research**

Our experimental results have contributed to the further development of a theory of multimedia instruction. We have proposed new design guidelines that exploit the power of inference and mental animation in learning from multimedia. The empirical result that our hypermedia manuals, whether on paper or on computer, are more effective than commercially available materials indicate that our guidelines offer a significant improvement over the conventional wisdom of designers of multimedia software. These results question widely-held beliefs about multimedia, and as a result of dissemination

will influence multimedia instructional design practice in the commercial and military sectors.

Our experimental results in the domain of meteorology have pointed to limitations in the comprehension of weather maps by naïve and novice students. These results suggest that instruction in meteorology needs to be improved so that causal principles are introduced in the context of practical tasks such as weather forecasting. In particular, students need to be taught how to weigh and integrate different causal principles in weather prediction.

## II. Impact of Technology Development

The eye tracking laboratories at Auburn and Santa Barbara are two of the very few research groups in the United States investigating the application of eye tracking to HCI and visualization research. We have developed various software programs for facilitating the analysis of eye movements easier, and for realizing gaze-contingent displays. These technologies have mainly been used in-house for supporting basic research. Since the focus of this research program was not developing and disseminating technology per se, the impact of the technology we have developed is indirect in terms of its support of basic research.

### 9. Results

Contrary to conventional belief, we found no evidence that students learn more from animations than from static diagrams of mechanical systems. We propose that this is because people can mentally animate static diagrams. Conditions that induce them to mentally animate static diagrams include question answering, reading text that describes how the parts of a machine move and viewing several diagrams (small multiples) showing different phases in the operation of the machine.

Contrary to conventional belief among multimedia designers, we found no evidence that students learn more from 3-d diagrams of mechanical systems compared to 2-d diagrams, that they are better at making predictions of device behavior from 3-d diagrams, or that they find 3-d diagrams more interesting or engaging. This suggests that additional expense involved in producing 3-dimensional diagrams is not justified, at least in the situations we have studied to date.

Visualizations that guide a problem solver's attention along causal pathways in a complex domain enhance attention to the relevant components of the problem and accuracy in problem solving, at the cost of increased response time.

Naïve students take longer to verify facts from more complex weather maps (showing more variables) compared to simpler weather maps. This suggests that when communicating to naïve individuals, visual displays should show only the relevant information and no additional information.

After taking a course in meteorology, novice students can articulate important causal principles in this domain, but have considerable difficulty in integrating and applying multiple causal principles to accurately predict a weather event. This suggests that instruction in meteorology needs to be improved so that causal principles are introduced in the context of practical tasks such as weather forecasting. In particular, students need to be taught how to weigh and integrate different causal principles in weather prediction.

## **10. Technology Transfer**

Our main means of facilitating technology transfer has been through research presentations at forums attended by scientists and engineers including those from industry and military. Through various presentations we have disseminated the results of our research at cognitive psychology, human-computer interaction, multimedia and interactive system design forums attended by scientists and engineers including those from industry and military.

Hegarty made a presentation at the workshop on Interactive Meteorology and Oceanography in August 2001, at the Naval Pacific Meteorology and Oceanography Center, San Diego, CA, thereby making Navy METOC personnel aware of results from our research. Narayanan presented results from this research at the Navy Center for Applied Research in Artificial Intelligence, Naval Research Laboratory, in May 2002, at the ONR Workshop on Attention, Perception and Data Visualization, George Mason University, in May 2002 and at the DARPA Augmented Cognition Conference in Austin, Texas in December 2001.

Hegarty also consulted with Navy Meteorology personnel regarding the design of stimuli for experiments in meteorology and Dr Ted Tsui at the Naval Research Laboratory in Monterey. She visited NRL in November 2001 and to collect data from expert meteorologists and to consult with these experts on the design of future research studies in the domain of meteorology.

This is a basic research project and therefore no actual products have been produced. However, our research has generated a set of guidelines for designing effective multimedia presentations which were communicated to another ONR-supported group -- Applied Physics Laboratory (APL), University of Washington -- and we had them design two hypermedia manuals through a subcontract. This mutually beneficial collaboration informs APL designers of the results of our research and enables them to construct multimedia visualizations that are based on empirically-validated cognitive principles.

## **11. Statistics**

UCSB: Graduate Students/Postdoctoral scholars supported at least 25% from this grant for at least 1 quarter:

Graduate Students:	Non-minority women: 4
	Minority man: 1



Non-minority man: 1

Post Doctoral scholar: Non-minority woman: 1

## 12. Journal Articles

Hansen, S., Narayanan, N. H. & Hegarty, M. (2002). Designing educationally effective algorithm visualizations. *Journal of Visual Languages & Computing*, 13, 291-317.

Hegarty, M., Kriz, S. & Cate, C. (in press). The Roles of Mental Animations and External Animations in Understanding Mechanical Systems. *Cognition & Instruction*.

Hegarty, M., Quillici, J., Narayanan, N. H., Holmquist, S., & Moreno, R. (1999). Multimedia Instruction: Lessons from Evaluation of a Theory-based Design. *Journal of Educational Multimedia and Hypermedia*, 8, 119-150.

Hegarty, M., Shah, P & Miyake, A. (2000). Constraints on using the dual-task methodology to specify the degree of central executive involvement in cognitive tasks. *Memory & Cognition*, 28, 376-385.

Kozhevnikov, M. & Hegarty, M. (2001a). A dissociation between object-manipulation and perspective-taking spatial abilities. *Memory & Cognition*, 8(3), 439-453.

Kozhevnikov, M. & Hegarty, M. A. (2001b). Impetus Beliefs as Default Heuristics: Dissociation between Explicit and Implicit Knowledge about Motion. *Psychonomic Bulletin & Review*, 8(3), 439-453. (peer-reviewed)

Miyake, A., Rettinger, D. A., Friedman, N. P., Shah, P & Hegarty, M. (2001). Visuospatial working memory, executive functioning and spatial abilities. How are they related? *Journal of Experimental Psychology: General*, 130(4), 621-640. (peer-reviewed)

Narayanan, N. H. & Hegarty, M. (1998). On designing comprehensible hypermedia manuals. *International Journal of Human-Computer Studies*, 48, 267-301.

Kozhevnikov, M., Hegarty, M. & Mayer, R. E. (2002a). Revising the Visualizer-Verbalizer Dimension: Evidence for two types of visualizers. *Cognition and Instruction*, 20, 47-77.

Narayanan, N. H. & Hegarty, M. (2002). Multimedia design for communication of dynamic information. *International Journal of Human-Computer Studies*, 57, 279-315.

## 13. Books or Chapters

Book:

Hegarty, M. Meyer, B & Narayanan, N. H. (2002). *Diagrammatic Representation and Inference*. Berlin: Springer-Verlag.

#### Chapters:

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#### 14. Technical Reports

14.1 Narayanan, N. H. & Hegarty, M. (2001). Multimedia design for communication of dynamic information. Technical Report CSSE01-02, Computer Science & Software Engineering Dept., Auburn University, Auburn, AL 36849, 33 pages.

## 15. Presentations

Hegarty, M. & Narayanan, N. H. (1996, February) Building hypermedia manuals for optimal comprehension of complex machines. Paper presented at the Office of Naval Research Workshop on Issues in Interactive Multimedia, New Mexico State University, Las Cruces, February, 1996.

Hegarty, M. & Narayanan, N. H. (1996, November) Designing hypermedia manuals to explain how machines work. Fourth ACM International Multimedia Conference, Boston, MA.

Hegarty, M. (1997, January). Understanding how machines work: Implications for multimedia design. Colloquium presented to the Cognitive Science Interdisciplinary Program, University of California, San Diego, CA.

Hegarty, M. (1997, April). Comprehension of text and diagrams: Implications for multimedia design. Talk presented to the Writing Program and IEEE Technical Communication Group, University of California, Santa Barbara.

Hegarty, M. (1997, April). Comprehension of text and diagrams: Implications for multimedia design. Colloquium presented to the Department of Psychology, University of Colorado, Boulder, CO.

Narayanan, N. H., & Hegarty, M. (1997, April) model based design of hypermedia presentations. ACM Human Factors in Computing Systems Conference (CHI).

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Kozhevnikov, M. Hegarty, M. & Mayer, R. E. (1998, August) Visual/Spatial abilities and problem solving in physics. Thinking with Diagrams '98, Aberystwyth, Wales.

Hegarty, M. (1999, April). Understanding machines from interactive multimedia manuals. Presented at the annual meeting of the American Educational Research Association, Montreal, Canada.

Kozhevnikov, M., Hegarty, M., & Mayer, R.E. (1999, April). The role of imagery in problem solving in physics. Presented at the annual meeting of the American Educational Research Association, Montreal, Canada.

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Hegarty, M., Narayanan, N.H., Cate, C & Holmquist, S. (1999, July). Understanding Machines from Diagrams, Text and Hypermedia Presentations. Presented at the Annual Conference of the Society for Applied Memory and Cognition. Boulder, CO.

Hegarty, M. Mental Animation (1999, October). Presented at the Cognitive Science Seminar, University of California, Berkeley.

Kozhevnikov, M. & Hegarty, M. (1999, November) Perspective taking ability is distinct from mental rotation ability. Presented at the Annual Meeting of the Psychonomics Society, November.

Hegarty, M. (1999, November). Mental Animation. Presented to the Department of Computer Science and Software Engineering, Monash University, November 1999.

Hegarty, M. (1999, December). Mental Animation. Presented to the Department of Architecture, University of Sydney.

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Hegarty, M. (2000, March) Understanding machines from multimedia and hypermedia presentations. Presented at Ricoh basic research center.

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Narayanan, N. H. & Hegarty, M. (2000, August). Communicating dynamic behaviors with mixed-mode presentations: Are interactive presentations better than static ones?" Presented at 1st international workshop on interactive graphical communication.

Hegarty, M. (2000, August). Capacity limits in diagrammatic reasoning. Paper presented at Diagrams 2000. Edinburgh, Scotland.

Narayanan, N. H. & Hegarty, M. (2000, August). Communicating dynamic behaviors: Are interactive multimedia presentations better than static mixed-mode presentations? Paper presented at Diagrams 2000. Edinburgh, Scotland.

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Kozhevnikov, M. & Hegarty, M. (2001, November). The role of spatial imagery in physics problem solving. Paper presented at the 42<sup>nd</sup> Annual Meeting of the Psychonomics Society, Orlando FL.

Hegarty, M. (2002, May). Spatial thinking in complex cognition. Colloquium presented to the Department of Psychology, University of California, Santa Cruz.

Hegarty, M. (2002, March). Spatial thinking in higher-level cognition. Presentation to National Research Council Committee "Support for Thinking Spatially". Santa Fe, New Mexico.

Hegarty, M (2002, August). Internal and external visualization. Paper presented at the Annual Meeting of the Cognitive Science Society, Fairfax, Virginia (August)

Hegarty, M. (2002, August) Discussant, Symposium on cognition of complex visualizations. Annual Meeting of the Cognitive Science Society, Vairfax, Virginia (August, 2002)

#### **16. Patents Issued and Pending**

None

#### **17. Honors**

Dr Hegarty was promoted from Associate Professor to Professor, effective July 1, 2000.

Mary Hegarty. Elected Fellow of the American Psychological Society, 2001.

#### **18. Additional References (not listed above).**

Hegarty, M. (1992). Mental animation: Inferring motion from static diagrams of mechanical systems. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 18, 1084-1102.

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## **19. Related Projects**

Hegarty, M. Individual Differences in Interacting with Hypermedia Manuals" Office of Naval Research (AASERT) 1997-2002, \$99,633.

Naryayanan, N. H. Eye Tracking Equipment for Analysis and Synthesis of Human Interactions with Hypermedia Information Visualizations, 2000-2001, \$127,200, Defense Universities Research Instrumentation Program (DURIP) Grant managed by ONR.